REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
04-15-2002

2. REPORT DATE
FINAL

3. DATES COVERED *(From - To)*
June 1, 2000- December 31,2001

4. TITLE AND SUBTITLE
Interpretation of Seafloor Characteristics in the Gulf of Aden

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-00-1-0748

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release
Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
See Attached

20020419 120

15. SUBJECT TERMS
Gulf of Aden; Bathymetry; Bottom Currents; Sediment Properties

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU		Stephen A. Swift

19b. TELEPONE NUMBER *(Include area code)*
508-289-2626

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI-Std Z39-18

Final Report to ONR
Interpretation of seafloor characteristics in the Gulf of Aden

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ABSTRACT

We collected multibeam bathymetry on two physical oceanographic cruises to the Gulf of Aden and a transit leg through the Gulf. These data have been edited, corrected for speed of sound and merged into a single data set with information from NGDC trackline bathymetry and ETOPO2 estimated water depths to fill in gaps. For the first time, these data define the shape of the seafloor along channels carrying saline overflow water from the Bab al Mandeb Strait into the Gulf of Aden above the Tadjoura Rift. The along-axis gradient and shape affect the degree and rate of mixing between overflow water and the ambient water in the Gulf.

LONG TERM GOALS

Interpretation of geotechnical properties and geomorphologic characteristics of the seafloor and near-subsurface sediments of the western Gulf of Aden requires the integration of paleoenvironmental, tectonic, geologic data and associated processes. Present geotechnical and geomorphologic interpretations are limited to published areal studies and qualitative observations. We will apply an integrated approach to demonstrate the spatial complexity of the shallow littoral and adjacent deep-water environments for the western Gulf of Aden. The final results will be presented to the Naval Oceanographic Office (NAVOCEANO) for implementation into operational products that are GIS based.

OBJECTIVE

The objective of this study is to provide a regional geologic interpretation of seafloor geotechnical composition, shallow subbottom stratigraphy and geomorphology. This study will examine the composition and configuration of the present day seafloor and near-subsurface and the mechanisms or processes that have produced these results. The nature and distribution of seafloor microtopography and geotechnical properties will be addressed. The effects of basin evolution and changes in sea level will be included to specifically address anomalous geologic conditions or geohazards. We will integrate temporal oceanographic or meteorological processes that may affect or change surface sediment cover.

APPROACH

To improve our understanding of the seafloor geotechnical properties and the processes responsible for the distribution of sediments, we initiated a collaboration with physical oceanographers at WHOI and RSMAS/UMiami and with geophysicists at SIO and LDEO. In 2001 the physical oceanographers had two cruises planned to the Gulf of Aden in order to study details of the Red Sea overflow current and the water masses that are formed by mixing with Gulf of Aden water. To understand the affects of seasonal changes in winds on the production of Red Sea water in the Gulf of Aden, they planned to conduct surveys in winter (February-March, NE monsoon) and summer (August, SW monsoon). In September, 2001, SIO and LDEO were scheduled conduct a joint seismic refraction/reflection survey from the R/V Ewing using OBSs along N-S lines at intervals along the Gulf of Aden. We made arrangements to acquire bathymetry and seafloor reflectivity collected on these cruises with hull-mounted multibeam systems. In addition,

we were to acquire sediment cores, high-resolution 3.5 kHz profiles, and the shallow sediment portion of the seismic reflection profiles. We planned to use these new data to extend the mapping done with the French backscatter and bathymetry data in the Tadjoura rift region that we had acquired in 2000. We also made efforts to locate results of physical properties measurements made on an extensive collection of sediment cores taken in the Gulf of Aden during 1971 by German scientists on the R/V Valdivia.

WORK COMPLETED

The grant funds were used to send a representative on the R/V Knorr 162-11 cruise to the Gulf of Aden (Mombassa, Kenya, to Seychelles; February 5 to March 15, 2001; chief scientist: William Johns, RSMAS). The purpose of this cruise was to conduct measurements of the outflow of high salinity water from the Red Sea and its mixing with ambient water in the Gulf of Aden. Water properties and mixing dynamics were studied south of the Bab al Mandeb Strait, CTD transects were made down the Gulf of Aden, and acoustically-tracked drifters were deployed. Our representative managed collection of multibeam bathymetry and digital 3.5 kHz echosounding profiles. During 2001, we also obtained multibeam bathymetry files from an R/V Knorr transit through the Gulf (KN 162-15; May 7-21; Seychelles to Istanbul; chief scientist: Audrey Rogerson, WHOI) and from a resurvey of summer water properties in the Gulf on the R/V Ewing (August 20-September 12; Djibouti-Djibouti; chief scientist: Amy Bower, WHOI). Part way through the cruise, Somali pirates attacked the R/V Ewing and subsequent operations were restricted to the central part of the Gulf. As a result of the attacks, the plans for a SIO/LDEO-led geology and geophysical survey of the Gulf of Aden on the following leg were canceled and the ship diverted elsewhere. We did not obtain the sediment cores and high-resolution seismic profiles from the Gulf that we had anticipated.

After each cruise we processed the multibeam bathymetry. Spurious navigation errors in the Seabeam data from the Knorr legs were located and removed. Sound velocity profiles computed by RSMAS from CTD observations were sorted into areas of similar vertical change. These data were used to convert travel time data to water depths. A major upgrade of the Hydrosweep system on the R/V Ewing was done just prior to the Gulf of Aden cruise and the LDEO technician was not familiar with the changes made. As a result the data acquired appear to contain artifacts. After the cruise, extensive efforts to correct roll-bias and to find correct water velocity profiles were able to reduce apparent bias in the outer beams that seems to originate with a systematic error during data collection. Data from the center beams appear to be of acceptable quality.

The multibeam data sets have been merged together with water depths from NGDC and ETOPO2. Not surprisingly, this was not simple. At any location where overlap occurs, water depths collected by each of the multibeam surveys differ from each other. In particular, the French data obtained on the 1995 Atalante cruise differ in small locations from Knorr and Ewing depths by up to several hundred meters. The largest errors occur where seafloor relief is steepest near the walls of the central Tadjoura rift. These differences appear to be related to differences in the way that the data were gridded into XYZ values and, perhaps, to the sound velocity profiles used. The Atalante water depths were computed with sound speed profiles determined based on shallow XBTs, whereas the Knorr and Ewing depths were computed using sound determined from full salinity and temperature profiles. Our final bathymetry product was obtained by gridding (cell dimension of 0.09 minute or ~165 m) multibeam files from each cruise separately and then averaging the contributions in each cell from the Atalante, Knorr, and Ewing legs. Gaps between multibeam coverage are filled with a gridded average of ETOPO2 and NGDC trackline depths.

We obtained copies of the hull-mounted 3.5 kHz echosounder on Knorr 162-11 in both digital and ship-board paper recordings. Records were not made on either Knorr 162-15 or Ewing 0110. The records appear to have sufficient amplitude range to reveal subbottom structure, but the high ship speed (10 knots) used during transits between CTD stations lengthened the distance between pings (~5 m/ping) and prevents resolution of features with lateral scales of less than 20-30 m.

We located paper records from the Valdivia coring operations at the sediment laboratory of GEOMAR in Kiel, Germany. In May of 2001, Amy Bower made a trip to University of Kiel to collaborate with physical oceanographers working in the Gulf of Aden. While there she visited the sediment core laboratory at GEOMAR and photocopied graphic logs for eleven of the Meteor and Valdivia cores whose records are stored there. The locations are shown in Figure 1. These logs include observations of basic physical properties (Table 1).

RESULTS

Most of the grant period was spent acquiring, correcting, and editing data from the three 2001 cruise legs to the Gulf of Aden. The cruise tracks for all bathymetry data are shown in Figure 1. Figure 2 shows the final gridded bathymetry for the Tadjoura Rift area west of 46°E where most of the water column observations were concentrated. The cruise tracks of the physical oceanography surveys proved too wide apart for the multibeam bathymetry and backscatter records to add significantly to our understanding of seafloor sediment conditions. The coverage of cores with physical properties measurements (Figure 1) improved with Amy's visit to Kiel but is also too sparse to map lateral variations in the basin.

There was one bright spot for seafloor studies in the 2001 cruise data. During the August leg on the R/V Ewing, Amy Bower surveyed a small region of the continental slope south of the Bab al Mandeb Strait where the channels leading south down the continental slope into the Tadjoura Rift bifurcate. The final bathymetry map in Figure 3 still contains north-south stripes that are artifacts of errors in the outer beam depths. Despite the artifacts, the general geometry of the junction is much clearer than that imaged with the French bathymetry. The primary channel leading south from the Red Sea turns eastward after exiting the Bab al Mandeb Strait and appears as the 320-360 m deep trough along 12°32'N in Figure 3. A second channel branches to the southeast in the figure across a sill at 260-280 m depth. Both channels are characterized by axial deeps with relief of 60 m or more and along-channel lengths of 2-4 km. In winter, high salinity water flows out of the Red Sea along these channels. Mixing with the ambient Gulf of Aden water entrains more water, so the flux increases downslope. The seafloor gradient along the channel axis and the width of the channel are critical factors controlling the mixing process and, thus, the downward growth in the outflow plume. Observations from current meter moorings in the two channels indicate that flow begins in the deeper east-west channel (along 12°32'N in Figure 3). As the season progresses, flow increases and the interface with the overlying ambient water rises until flow can cross the sill and spill into the NW-SE channel. Deeper on the continental slope, the interface remains below the top of the channels walls. Current observations indicate that the entrainment process is fed by ambient water from deeper depths within the channel. In winter, then, strong downslope flow of high salinity water along the floor of the channel axes is overlain by flow directed upslope within the channel walls. Clearly, the presence and topography of the channels, which were formed by rift tectonics over the last 1-2 Myrs, is a key element affecting water fluxes out of the Red Sea and in the early temperature/salinity/density evolution of the plume of high-salinity water in the Gulf of Aden.

We examined the 3.5 kHz records from Knorr 162-11 to look for evidence of sediment reworking. We found bedforms with wavelengths of <1 km located at 480-540 m water depth on the western flank of the eastern most channel (near 12°10'N, 44°10'E) just above the edge of steep slope into the Tadjoura rift. While flow associated with mesoscale eddies or internal waves may have created these bedforms, their proximity to the channel suggests that they are more likely related directly to either the high-salinity outflow or the upslope return flow associated with winter currents in the channels. Away from the slope channels the evolution of the Red Sea overflow water is strongly affected by the presence of mesoscale eddies. Current velocities measured with hull-mounted ADCPs and current drifters clearly image circular eddies with diameters stretching north-south across the width of the Gulf of Aden. In the western Gulf, water properties indicate that the most active circulation occurs above ~1200 m with velocities decreasing downward from 100 cm/s near the sea surface to 20 cm/s near the base of the eddies. The western-most eddy appears to be topographically trapped, so we looked at 3.5

kHz profiles collected on KN162-11 in water depths above ~1 km. At the scales resolvable (>20-30 m), we found no evidence of seafloor bedforms formed by reworking of sediments. Smaller scale bedforms could be present.

IMPACT/APPLICATIONS

The Gulf of Aden is a relatively-young continental rift, so most of the seafloor features are formed by volcanic, faulting, and subsidence (and uplift) processes driven by tectonic forces. Despite the dry climate and absence of rivers, published sediment analyses indicate that the seafloor is covered with soft carbonate-rich mud at water depths >0.5-1 km grading upwards into carbonate sand on the upper continental slope. On the continental shelf, sand and gravel are most common with occasional patches of mud. In deep water, the French seafloor backscatter maps show that the major exceptions are young volcanic terrain and steep rift-related fault topography on which little sediment accumulates. Data collected in the last year indicate that currents also have an affect, although their impact appears to be localized.

The seafloor around the channels carrying Red Sea overflow water into the Gulf of Aden have been most affected by currents. The axes of the channels is swept clear of sediments with small and temporally-varying occurrences of carbonate gravel. The channel floor is crystalline basement or a hard, chemically-cemented sediment layer. The lower walls of the channel are likely as hard being comprised of exposures of outcrops of older, consolidated sediment layers. As the channels cross the slope, loose gravel and sand blanket the upper walls of the channels and extend onto the seafloor surrounding the channels. Here, we also observe bedforms above the rift walls indicating water flow associated with the outflow has reworked the seafloor probably producing coarser, sediment with lower water contents. Based on the presence of rapidly rotating eddies reaching from the Yemen continental shelf to the Somali shelf, we predict that seafloor sediments from the shelf edge down to 1000-1400 m are also reworked by weak, eddy-driven bottom currents. Sampling so far has not been done to test this hypothesis and the limited data we have collected failed to confirm our interpretations. Normal canyon cutting processes do not seem to have been as active as on other continental margins - probably due to the arid climate and lack of river borne sediments.

TRANSITIONS

Bathymetry compiled under this grant has been shared with many investigators. In the summer of 2001 a gridded data set was provided to A. Bower and W. Johns for planning their second sampling leg in August. The bathymetry closely affects mixing and plume evolution. We have provided the physical oceanographers with topographic profiles along the channel axes and along the crest of the rift walls. We also made this version available to N. Driscoll, P. Huchon, and others involved with the planning of the geophysical leg that was scheduled for September 2001 but was canceled. Since September 2001, we have finalized a compilation of gridded bathymetry and made it available to other investigators via out anonymous ftp site.

Multibeam files and gridded bathymetry have been transferred to the Naval oceanographic Office (Code 92, Peggy Schexnayder, point-of-contact).

RELATED PRODUCTS

Identified above.

Table 1. Physical properties measured in sediment cores obtained in 1971 by the R/V Valdivia.

Core	Longitude (°E)	Latitude (°N)	Water Depth (m)	Core Length (m)	Wet density (gm/cc)			Water content (%)		
					0 cm	100 cm	200 cm	0 cm	100 cm	200 cm
118K	42.1350	15.0267	402	1.95	1.35	1.41	1.41	56.3	54.4	52.65
216G	46.0983	12.1267	2306	2.80	1.24	1.33	1.37	65.1	55.9	50.6
219P	45.5383	11.8017	1729	6.25						
275K	46.7767	12.3917	2005	2.00	1.33	1.53	1.46	55.1	43.1	45.36
279K	48.3083	11.5333	1336	2.35	1.33	1.47	1.43	54.7	45.7	43.99
280K	48.2583	11.7467	2106	2.76	1.31	1.46	1.53	57.0	43.7	41.4
281K	48.3217	12.0133	2148	2.00	1.35	1.41		53.7	46.7	
284K	46.9967	13.0283	1622	2.63	1.34	1.45	1.48	54.9	40.4	44.1
285K	47.2283	12.8350	1908	2.65	1.30		1.51	56.6	42.0	41.0
286K	47.3800	12.7433	1287	1.55	1.42	1.46		47.2	44.9	
293K	43.3467	11.9200	1054	2.72	1.36	1.40	1.46	55.5	51.5	46.0

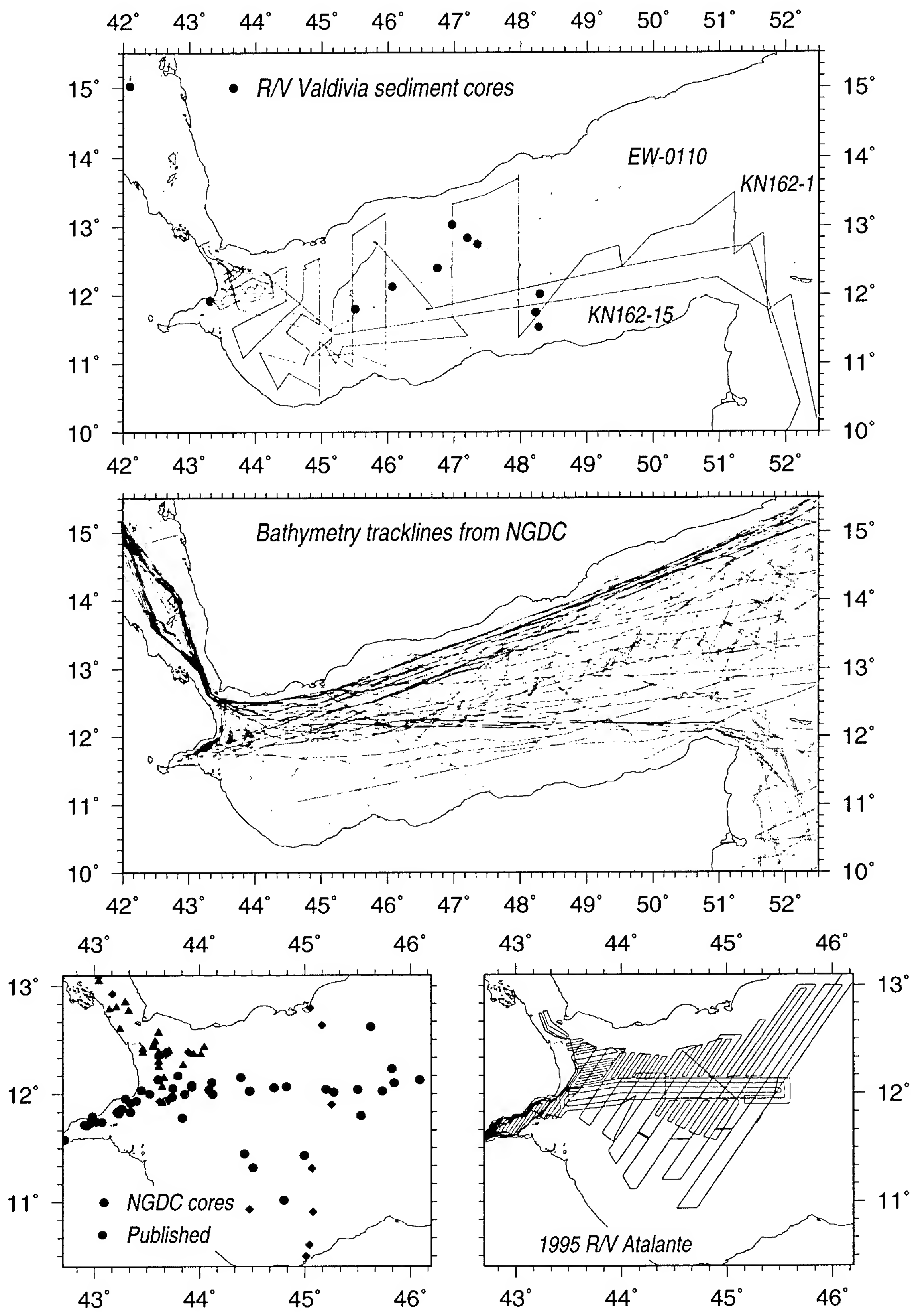

Figure 1. Locations of tracklines and sediment samples used in compilation of bathymetry and sediment properties in the Gulf of Aden.

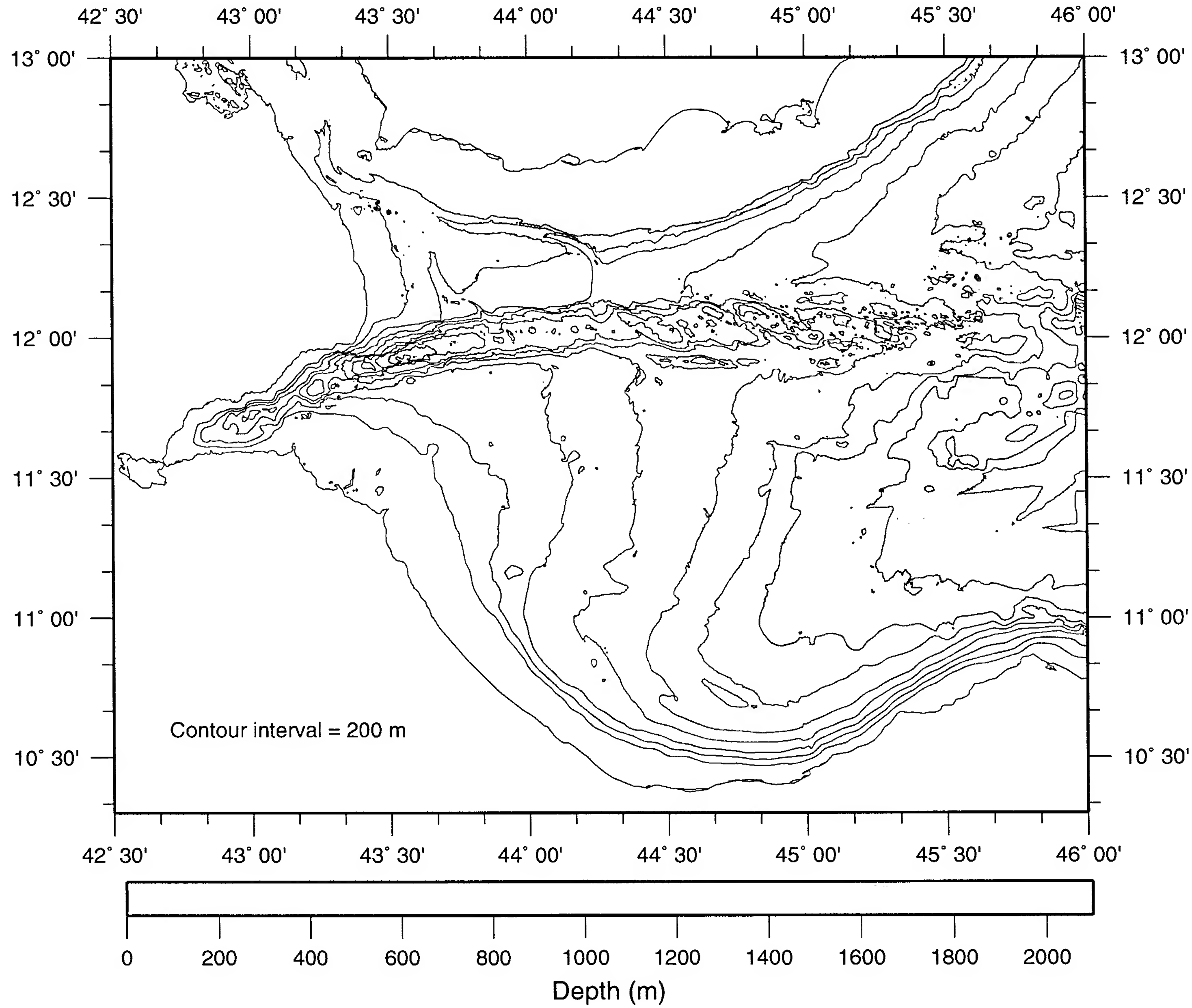

Figure 2. Gulf of Aden bathymetry from multibeam cruises (Atalante, Kn 162-11, Kn162-15, Ew0110) merged with ETOPO2 and NGDC trackline depths.

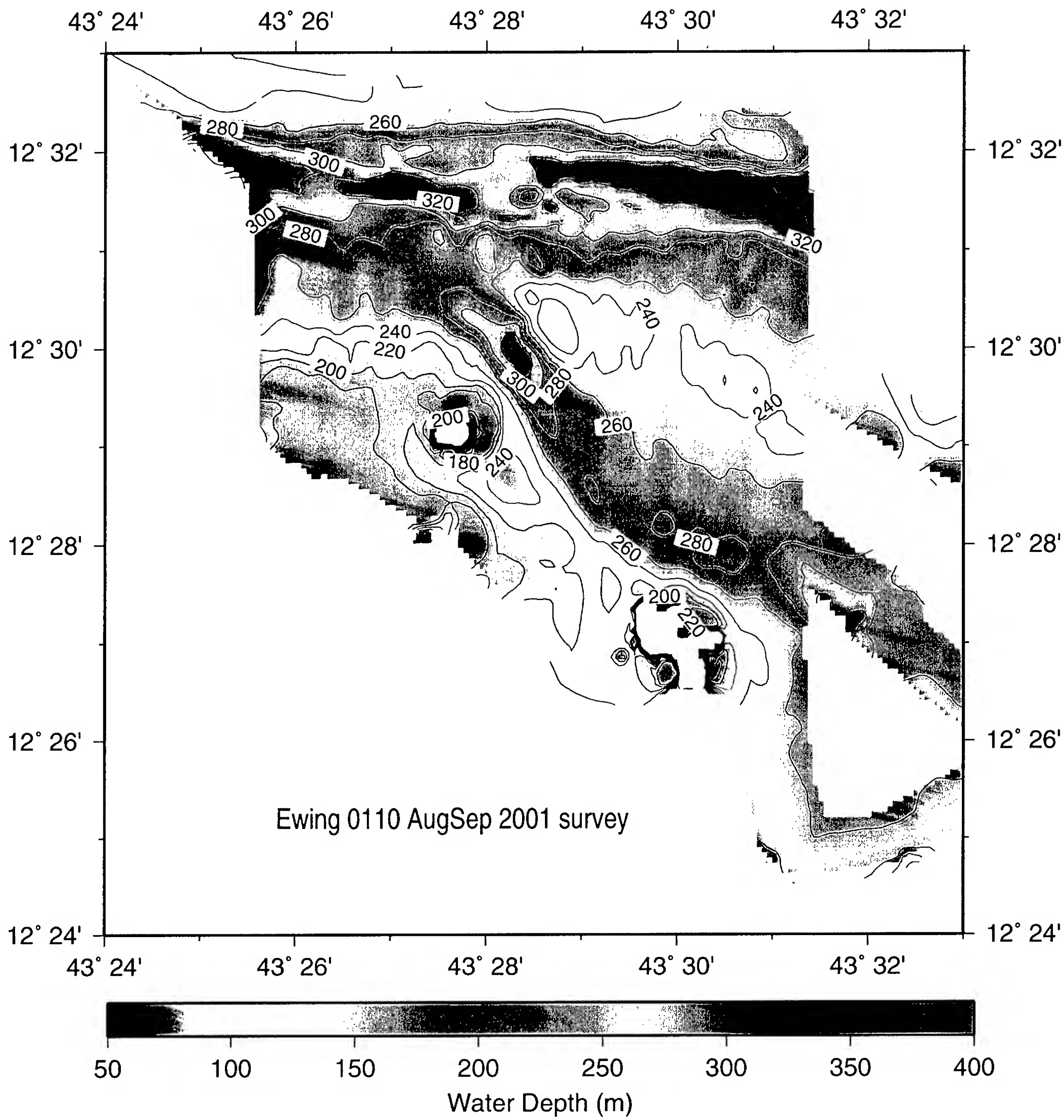

Figure 3. Detailed bathymetry (from R/V Ewing 0110, A. Bower) located south of Bab al Mandeb Strait showing bifurcation of seafloor channels that carry Red Sea overflow water.